

Shock heating by FR I radio sources in galaxy clusters

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ABSTRACT

Feedback by active galactic nuclei (AGN) is frequently invoked to explain the cut-off of the galaxy luminosity function at the bright end and the absence of cooling flows in galaxy clusters. Meanwhile, there are recent observations of shock fronts around radio-loud AGN. Using realistic 3D simulations of jets in a galaxy cluster, we address the question what fraction of the energy of active galactic nuclei is dissipated in shocks. We find that weak shocks that encompass the AGN have Mach numbers of 1.1-1.2 and dissipate at least 2% of the mechanical luminosity of the AGN. In a realistic cluster medium, even a continuous jet can lead to multiple shock structures, which may lead to an overestimate of the AGN duty cycles inferred from the spatial distribution of waves.

Key words:

1 INTRODUCTION

There is increasing evidence from deep X-ray observations for shock waves from radio-loud active galactic nuclei (AGN) in the central cores of galaxy clusters (e.g. McNamara et al. (2005)). Examples are the (weak) shocks in M87 (Forman et al. 2005, Simionescu et al. 2007), Hydra A (Nulsen et al. 2006) and Perseus (Fabian et al. 2006). Using deeper CHANDRA data of the Virgo cluster, Forman et al. (2006) confirmed the presence of a weak shock at 14 kpc and determined its Mach number as $M \sim 1.2$. This shock was confirmed spectroscopically using XMM-Newton data by Simionescu et al. (2007). Sanders & Fabian (2006) report isothermal shocks in Abell 2199 and 2A 0335+096 with Mach numbers of ~ 1.5 . Shock waves have also been detected in the periphery of the low-power isolated radio-galaxy NGC 3801 (Croston et al. 2007) and a strong shock has been associated with the expanding FR I radio galaxy in Centaurus A (Kraft et al. 2003).

The detection of shocks around FR I sources has led to the suggestion that most, if not all, radio galaxies go through a phase that is associated with shock heating by a supersonically expanding radio source. Croston et al. (2007) have estimated that the energy stored in the shocked shell is equivalent to the thermal energy within ~ 11 kpc of the galaxy centre and a factor 25 larger than the inferred $p dV$ work required to inflate the radio lobes. This suggests that in the early phases of radio-source evolution, the energy trans-

fer from the AGN to its environment is dominated by shock heating.

Nulsen et al. (2006) made the following estimate for the heat input into the ICM by shock waves: The heat per unit mass generated by a shock is given by

$$\Delta Q \sim T \Delta S = E \Delta \ln p / \rho^\gamma, \quad (1)$$

where E is the specific thermal energy, p the pressure and ρ the density of the gas. Thus, the fraction of the thermal energy that is dissipated, $\Delta Q/E$, is given by the jump of $\ln p / \rho^\gamma$ in the shock. Three weak shocks are visible in the X-ray image of M87. For the innermost shock at ~ 3.7 kpc a Mach number of 1.4 has been inferred, which implies a heat input of $\Delta Q/E \approx 0.022$ and a shock age of 2.4×10^6 yrs. Obviously, the heat input of this shock is tiny. However, two more shocks have been identified at larger radii that require several times more energy. Thus, a shock of comparable strength to the 3.7 kpc shock may well occur every $\sim 2.5 \times 10^6$ y. The cooling time of the gas at 3.7 kpc is $\approx 2.5 \times 10^8$ yrs, so that there is time for ~ 100 such shocks during the cooling time. Therefore, the combined heat input from ~ 100 of these shocks is more than enough to make up for radiative losses from the gas.

In this Letter, we investigate what fraction of the jet energy is dissipated in shocks around the supersonically expanding radio source. Using a hydrodynamical simulation of jets in a realistic cluster set-up and a shock finding algorithm, we quantify the properties of the shock and the effect on the intracluster medium.

2 METHOD

The initial conditions of our simulation are based on a rerun of the S2 cluster from Springel et al. (2001), whose properties are sufficiently close to a typical, massive, X-ray bright cluster with a mass of $M \sim 7 \times 10^{14} M_{\odot}$ and a central temperature of 6 keV. The cluster appears as a classical, relaxed cooling flow cluster in X-rays. Its density rises steeply in the centre, and the profile is very similar to the density profiles reported in Vikhlinin et al. (2006). The setup is the same as used in Heinz et al. (2006). The output of the GADGET SPH simulation serves as the initial conditions for our simulation. We use the FLASH code (Fryxell et al. 2000) which is a modular block-structured adaptive mesh refinement code, parallelised using the Message Passing Interface. It solves the Riemann problem on a Cartesian grid using the Piecewise-Parabolic Method. Our simulation includes 7×10^5 dark matter particles. For the relatively short physical time of the jet simulation (25 Myrs), radiative cooling and star formation are neglected, though they were included in the constitutive SPH simulation.

The computational domain is a 2.8 Mpc³ box around the cluster's centre of mass. The maximum resolution at the grid centre corresponds to a cell size of 174 pc, implying 11 levels of refinement. The simulations presented in this letter were performed assuming an adiabatic equation of state with a uniform adiabatic index of $\gamma = 5/3$.

The jet is injected through a nozzle placed at the centre of the gravitational potential, coincident with the gas density peak of the central elliptical galaxy. The nozzle is modeled as two circular back-to-back inflow boundaries 2 kpc or 12 resolution elements in diameter. The nozzle faces obey inflow boundary conditions fixed by the jet's mass-, momentum-, and energy fluxes. This treatment avoids the entrainment of cluster gas into the jet which is unavoidable in simpler schemes where the jet is approximated by injecting mass, momentum, and energy into a finite volume of the cluster that contains thermal gas and is part of the active computational grid. We were thus able to separate cleanly jet fluid and cluster fluid in order to study the heat input into the ICM only. The jet is centred on the gravitational potential of the cluster and follows the (slow) motion of the cluster through the computational domain.

The jet material is injected equally in opposite directions with velocity $v_{\text{jet}} = 3 \times 10^9 \text{ cm s}^{-1}$ and an internal Mach number of 32. The jet power of the simulation presented in this letter was chosen to be $W_{\text{jet}} = 3 \times 10^{45} \text{ erg s}^{-1}$, corresponding to a rather powerful source. Comparing this luminosity with the sample of cavity systems studied by Bîrzan et al. (2004), the jet power in our simulation is at the extreme end of those observed and well above that cited for M87 (Allen et al. (2006)). However, even such powerful sources assume FR I morphologies in dense clusters such as this one (see, e.g., Perseus A). Even though Perseus A is inferred to have a mean power output of $\sim 10^{44} \text{ erg s}^{-1}$ (Sanders & Fabian 2007), its peak luminosities are likely to be significantly larger. Hercules A has a power of $1.6 \times 10^{46} \text{ erg s}^{-1}$ as implied by the large-scale shocks found around it (Nulsen et al. 2005; McNamara et al. 2005) but still exhibits an FR I/II morphology. In our simulation, we chose

such a high luminosity to ensure that the jet is able to push through the dense gas of the central galaxy.

The shocks in our simulation are detected using a multi-dimensional shock detection module adopted from the sPPM code¹ based on pressure jumps across the shock. The basic algorithm evaluates the jump in pressure in the direction of compression (determined by looking at the velocity field). If the total velocity divergence is negative and the relative pressure jump across the compression front is larger than some chosen value ($\Delta p/p \geq 0.25$), then a zone is marked as shocked. Using the jumps across the shock in the 3 velocity components, we get the x -, y -, and z -components of a unit vector pointing in the direction of the velocity jump, hence in the direction normal to the shock front. We now project the pre- and post-shock velocities onto the shock normal. The upstream and downstream pressure, the upstream velocity and density are then written out. We have tested this shock detection algorithm with one- and two-dimensional shock tube problems and found that the jumps in pressure and density are reproduced very well. The shock structures in a slice through the central regions of our computational domain are shown in Fig. 1.

3 RESULTS

We have simulated a jet that resembles a FR I source in a realistic cluster environment. Our simulation reproduces the shock structure in the inner $\sim 100 \text{ kpc}$ of the cluster around an AGN with FR I morphology. One can see how the jet inflates bubbles that break off and start to rise through the cluster medium. This morphology resembles many of the low-power AGN that are observed to inflate bubbles at the centres of cooling flow clusters.

Fig. 1 reveals two kinds of shocks: At the working surface of the jet, i.e. at the point where the jet impacts the ambient medium, there is a very strong shock wave. In the first million years after the start of the jet, this shock wave has Mach numbers with respect to the ICM of > 30 . The normal of this shock surface is equal or close to the direction of the jet and does not encompass the entire jet region, contrary to the outer shock that is described below. Later on, as the ICM near the jet gets hotter, the Mach number of the strong inner shock decreases to close to $\sim 8 - 10$. When motions of the ambient medium cause the jet to break off or to change direction, this shock can detach and a new working surface forms. As the jet jitters and ambient material moves into the jet, multiple shock fronts develop in the region close to the AGN. This leads to multiple shock features, as one can see in the bottom left panel of Fig. 1. In our simulation, we see that a *continuous* jet can lead to multiple shock fronts as those observed in M87 and other clusters. Hence, the existence of multiple shock fronts does not necessarily imply an intermittency of the AGN.

¹ S.E.Anderson and P.R.Woodward, World Wide Web <http://www.lcse.umn.edu/research/sppm>, Laboratory for Computational Science and Engineering, University of Minnesota (1995).

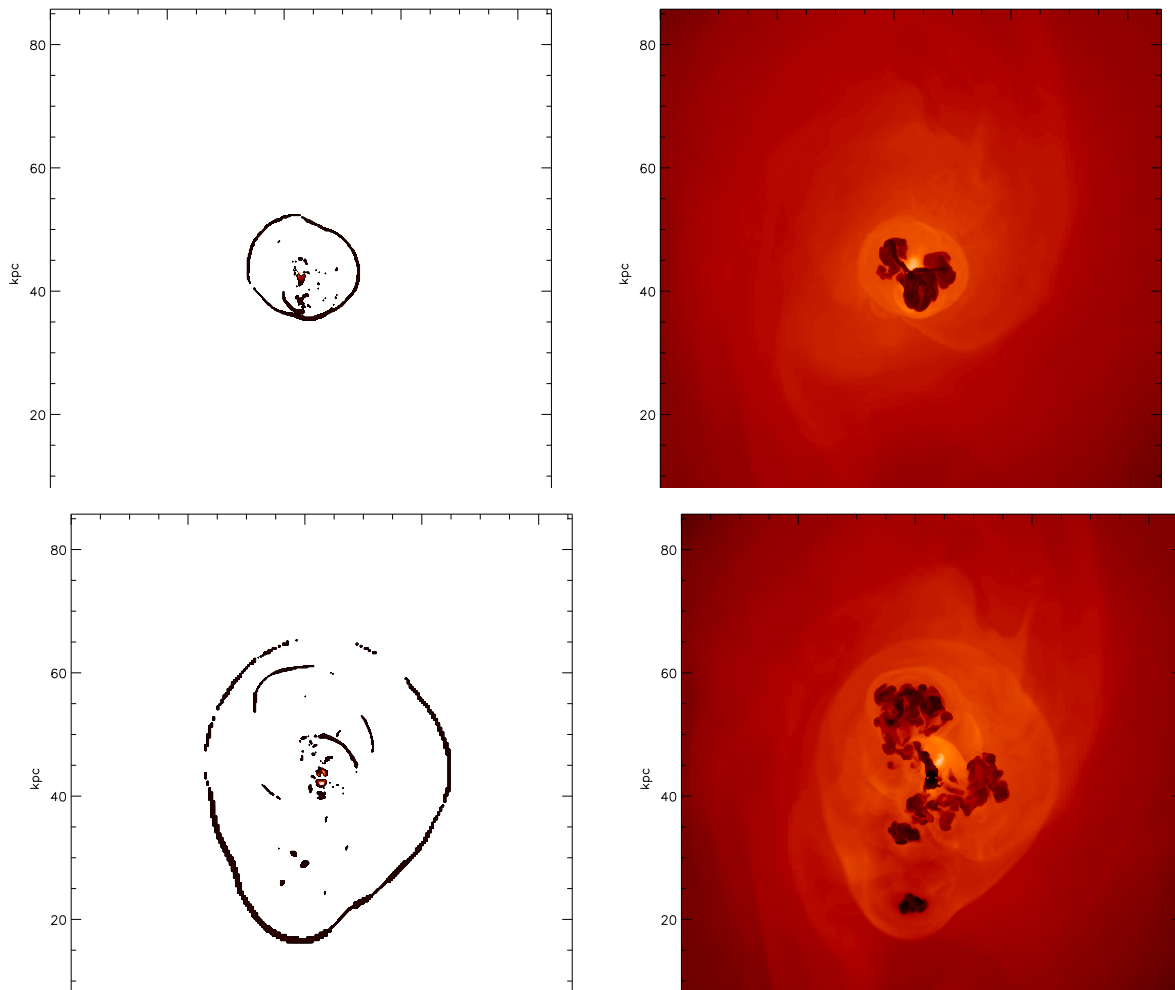


Figure 1. Slices through the cluster centre showing the shocks (left) and the gas density (right) at 5 Myrs and 15 Myr after the start of the jet. Shown is only the central part of the computational domain. The entire computational domain represents a volume of 2.8 Mpc^3 .

The second kind of shock is a weak and nearly spherical shock that travels from the point of the injection region outwards through the cluster. The Mach number of the outer shock remains at fairly constant values of around 1.1 - 1.2 for the largest part of its propagation through the core of the cluster. The pressure jump across a shock of $M = 1.2$ is 1.55. The outer shock is a pressure wave that is driven by the additional pressure from the injected gas in the core of the cluster. This is different from the strong, inner shock that is driven by the ram pressure of the jet. After about 10 Myrs the outer shock becomes prolate in the direction of the jet. As the bubbles rise mainly in the jet direction, the pressure also increases preferentially in the direction of the jet. The Mach number is slightly higher in the direction of the jet than at the sides of the outer shock front.

Next, we wish to compute the total energy thermalised in the shock front. One can write for the thermal energy flux generated at the shock:

$$F = [e_d - e_u(\rho_d/\rho_u)^\gamma] v_d, \quad (2)$$

where the subscripts d and u denote down- and upstream

quantities, respectively, e is the thermal energy density, ρ gas density and v velocity. The second term inside the brackets subtracts the effect of adiabatic compression suffered at a shock. The total thermalised energy input per time (by shocks) divided by the mechanical luminosity of the jet is shown in Fig. 2. About 2% of the mechanical luminosity of the jet are converted lastingly into internal energy. The properties of the outer shock are found to be relatively insensitive to the mechanical luminosity of the jet. The inner, strong shocks are much more efficient at generating energy because their Mach number is much higher. However, their area is relatively small and thus they may be important for the interstellar medium of the host galaxy, but they are unlikely to have a significant effect on the thermal state of the ICM. The properties of the inner shock depend also quite sensitively on the exact jet parameters and to some degree on the numerical resolution of our grid. Meanwhile, the properties of the outer shock are not sensitive to the numerical resolution and appear converged. We note that the timescale and geometry of the initial energy release is important for the computation of the energy deposited in the ICM or interstellar medium. If the same total energy were injected in the form of thermal energy in pressure equilibrium with the

surroundings, the amount of energy transferred to the ICM in the form of shocks would be very different. Even taking into account the uncertainties of our jet model, the approach presented here is much more realistic than schemes in which the energy is injected in pressure equilibrium.

The total increase in internal energy per unit time of the ambient medium (i.e. excluding the jet material) within the outer shock divided by the total mechanical power of the jet is shown in Fig. 3. We see that for the first 15 Myrs of the AGN activity, a bit more than 30 % of the injected energy has been converted to thermal energy in the inner core. This is much more than what has been thermalised by the outer shock. The temperature increase in the cluster core is mainly caused by $p dV$ work from the expanding bubbles. While the shocks thermalise only a few per cent of the jet energy, this also raises the entropy of the cluster. On the other hand, $p dV$ work by the expanding bubbles is adiabatic until the gas motions induced by the rising bubbles are dissipated by viscous processes (Nulsen et al. 2006). Yet, a succession of shocks can be sufficient to offset the radiative cooling of the entire ICM, as only 4-5 shock fronts that are permanently present lead to a conversion of ~ 10 % of the jet energy.

Clearly, magnetic fields can alter the dynamics of the jet and the radio lobes. As shown in Ruszkowski et al. (2007), large-scale cluster magnetic fields tend to drape themselves around the rising bubbles and can suppress the fragmentation of the bubbles. The ensuing dynamics can be different from the dynamics modelled here, but the outer shock structure is unlikely to be substantially different. In the presence of a physical viscosity with values close to the Spitzer value, the dissipation of the outer, weak shocks can be higher than what we find in our simulation (see also Brüggen et al. 2005; Ruszkowski et al. 2004).

We have presented a single simulation of a shock that has been produced by a FR I jet. Obviously, there are a lot of parameters that can be varied. However, these kind of simulations are very expensive; on NAS Columbia a single simulation took more than 12,000 CPU hours (on 64 processors). Hence, we chose one exemplary case that reproduces properties that match observations such as those in Hercules or M87 (despite wide discrepancies in jet powers). In the long term, a proper parameter study ought to be conducted.

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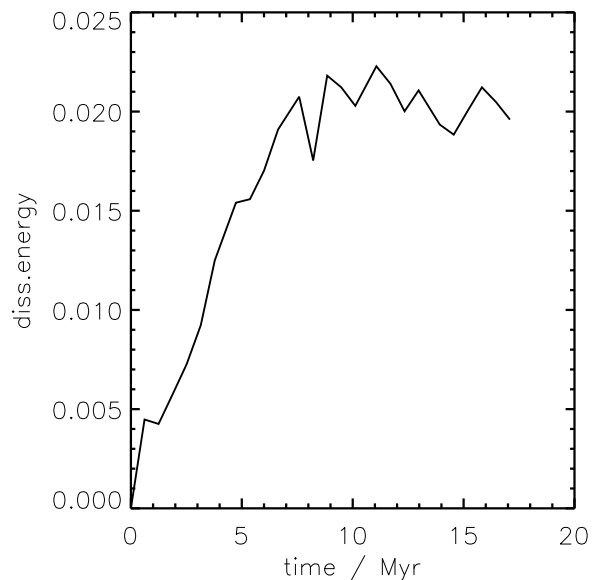


Figure 2. Plot of the energy generated at the outer shock surface per time divided by the mechanical luminosity of the jet.

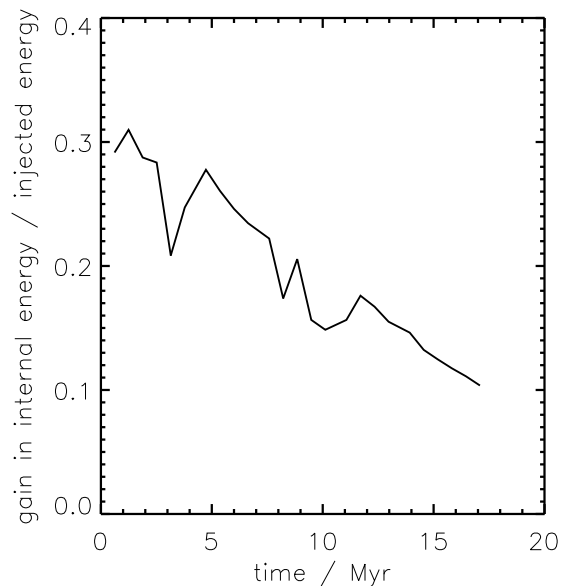


Figure 3. Increase in internal energy of the ambient medium (i.e. excluding the jet material) within the outer shocks divided by the total mechanical energy injected so far.

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